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Injury and Mortality of Warmwater Fishes Immobilized by Electrofishing

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Abstract.—Most studies of injury associated with electrofishing have focused on salmonids; few have given attention to warmwater fishes. Under controlled laboratory conditions, we treated bluegill *Lepomis macrochirus*, channel catfish *Ictalurus punctatus*, and largemouth bass *Micropterus salmoides* of various sizes to duty cycles ranging from 1.5% to 100%. This range of duty cycles represented continuous DC and pulsed-DC frequencies ranging from 15 to 110 Hz and pulse durations of 1 to 6 ms. At each duty cycle, fish were exposed to power densities in excess of those required to immobilize them within 3 s, and we subsequently determined the incidence of hemorrhage, spinal injury, and mortality. Incidence of hemorrhage averaged 3% (range, 0–25%), differed among species, and was not related to duty cycle or fish size. Incidence of spinal injury averaged 3% (range, 0–22%) and mortality averaged 10% (range, 0–75%); both differed among species and were related to duty cycle, fish size, and interactions among these variables. Largemouth bass was the species most vulnerable to hemorrhage, spinal injury, and mortality, channel catfish the least vulnerable; bluegills exhibited effects that were intermediate. Small centrarchids were especially susceptible to mortality. Fish tetanized by the electrical treatment were more likely to experience injury and mortality than fish that were only narcotized. However, mortality was not related to the injuries studied because hemorrhage and spinal injuries were similar in fish that survived electroshock and in those that died. We suggest that electrofishing with intermediate to high duty cycles could reduce electrofishing-induced injury and mortality to warmwater fish. Additionally, the power output and electrode system should be managed to induce narcosis and prevent tetany and to avoid the large peak powers required to immobilize small individuals.

Electrofishing is a widely used, accepted, and effective method for collecting freshwater fishes (Simpson and Reynolds 1977; McMichael et al. 1998; Vaux et al. 2000). Historically, studies have shown that exposure of fish to electric current can lead to harm, particularly tissue hemorrhage and spinal injury, and can even cause immediate or delayed mortality (Hauck 1949; Spencer 1967; Sharber and Carothers 1988). Injured fish do not always suffer long-term physical handicap or die because injuries often heal (Horak and Klein 1967; Hudy 1985; Schill and Elle 2000). However, survival may be indirectly influenced by the adverse effects of electric shock on behavior, health, growth, and reproduction (Gatz and Adams 1987; Mesa and Schreck 1989; Muth and Ruppert 1996). These adverse effects have prompted claims that studies of fish populations might be seriously compromised by the use of electrofishing (e.g., Bardygula-Nonn et al. 1995). For example, failing to minimize electrofishing-induced injury and mortality in fish collected for mark–recapture studies may lead to inflated population estimates or deflated exploitation estimates (Pratt 1955; Barrett and Grossman 1988). Moreover, the detrimental effects of electrofishing may severely affect threatened or endangered fish populations (Barrett and Grossman 1988). Nevertheless, studies have shown no or limited population-level effects (Schill and Beland 1995; Kocovsky et al. 1997; Carline 2001). Because of concerns regarding electrofishing injury and mortality, some researchers have suggested that electrofishing techniques and theory require further examination (e.g., Reynolds 1996).

The way in which electrical power is presented (i.e., AC, continuous DC, or various forms of pulsed DC) affects how a fish's nervous system is stimulated (Lamarque 1990; Sharber and Black 1999), and possibly the incidence of injury and mortality. The AC waveform is thought to be most injurious to fish (Reynolds 1996). Conversely, continuous DC is often regarded as the least injurious waveform (Lamarque 1990; Reynolds 1996). Fish mortality rarely occurs because of DC electroshock, but physical injuries and physiological trauma have been noted, although often un-

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detectable externally (Sharber et al. 1994). Pulsing the delivery of DC helps increase field strength by producing large bursts of peak power that are of short duration and intercalated with recovery periods that allow the transformer and capacitor components time to store the energy required for the next burst (Novotny 1990). By releasing the stored energy in short bursts, pulsed DC is capable of delivering higher voltage because the instantaneous power level is increased substantially above the mean power. Because of increased field strength, pulsed DC can produce effects that are more severe than continuous DC (Reynolds 1996).

Pulsed DC waveforms are composed of a pulse frequency (pulses per time; Hz) and pulse duration (time on for 1 pulse; ms), and are often described in terms of duty cycle (i.e., 100 × pulse frequency × pulse duration/1,000 ms; Reynolds 1996). Thus, a pulsed DC 110 Hz, 6 ms waveform has a 66% duty cycle, or 100 × 110 Hz × 6 ms/1,000 ms. Vibert (1967) recommended that fish should be collected with low-frequency settings to minimize injury. Sharber et al. (1994) reported that incidence of spinal injury to rainbow trout *Oncorhynchus mykiss* increased with changes in pulse frequency from 15 to 512 Hz. Similarly, Dolan et al. (2002) found that incidence of hemorrhage in black crappies *Pomoxis nigromaculatus* was related to pulse frequency. Sharber et al. (1994) recognized the potential for incidence of injury to be significantly reduced by employing low-energy, low-frequency, pulsed DC waveforms. In contrast, Lamarque (1990) indicated that electrical settings consisting of short-pulse durations were the most injurious to fish. Little attention has been given to duty cycle, which fuses pulse frequency and pulse duration into one measure.

Tetany (fish immobilized, muscles rigid, and no breathing motions), which can produce injuries from associated severe muscle contractions (Lamarque 1990), is the last stage in a series of three general behavioral responses recognized in fish exposed to electroshock. Tetany is preceded by narcosis (fish immobilized, muscles relaxed, still breathing), and fright (sporadic swimming). Many researchers (e.g., Vibert 1967; Lamarque 1990) have suggested that injuries can be avoided if electrofishing equipment is operated at voltages strong enough to induce narcosis but not tetany.

Most injury and mortality experiments have been conducted on salmonid species, and with few exceptions, little is known about the effect of continuous DC and pulsed DC on warmwater fishes. In one study, continuous DC was determined to be less injurious than AC to largemouth bass *Micropterus salmoides*, bluegills *Lepomis macrochirus*, and channel catfish *Ictalurus punctatus* (Spencer 1967). Barrett and Grossman (1988) found no relation between DC electroshock and short-term survival of mottled sculpin *Cottus bairdi*. The AC waveform did not lead to high rates of mortality in several warmwater fish species researched by Schneider (1992). Van Zee et al. (1994) suggested that pulsed AC was less harmful to largemouth bass, bluegill, and smallmouth bass *Micropterus dolomieu* than pulsed DC or unmodified AC. Also, Bardygula-Nonn et al. (1995) suggested that pulsed DC did not cause high mortality in several centrarchid species, although incidence of mortality was greatest in small fish. Most studies of warmwater species have focused on whether fish are injured or die following electrofishing but have rarely addressed the operational requirements needed to minimize harmful effects. The objective of this study was to identify duty cycles that minimize risk of injury and mortality to selected warmwater fishes, and thereby identify methodology for reducing the effects of electroshock to fish populations.

Methods

Electroshock Testing

Test tank and power source.—All testing was conducted from March 1999 to February 2000 under controlled conditions. Experimentation was performed in a polyethylene tank (2.0 m long, 0.5 m wide, 1.0 m deep) filled to a depth of 10 cm with well water. The cross-sectional profile of the tank was covered in its entirety with two, 1.6-cm thick aluminum plate electrodes positioned 65 cm apart, perpendicular to the longitudinal axis of the tank. Electricity for most treatments was supplied to the tank via a Smith-Root 15-D POW electrofisher (Smith-Root, Inc., Washington) modified to allow continuous rather than discrete voltage control and supplemented with smoothing capacitors to eliminate spikes and reduce ripples at the peak of pulses. A Coffelt Mark X electrofisher (Coffelt Manufacturing, Arizona) was used to apply a Coffelt trademark pulse train (see below). Conditions within the tank produced a homogeneous electrical field with a constant voltage gradient. Homogeneity within the electrical field was verified through direct voltage gradient measurements made with a probe similar to that described by Kolz (1993). Specific conductivity (C_s; μS/cm) and ambient water temperature (T_w) were recorded with a YSI 30/10 FT meter (Yellow Springs Instruments, Ohio). The meter read C_s at specific temperature (T_s; 25°C). Ambient water conductivity (C_w) was estimated from specific conductivity, specific temperature, and ambient water temperature (Reynolds 1996):

$$C_w = \frac{C_s}{1.02^{T_s - T_w}}. \qquad (1)$$

Electrical treatments and test fish.—We selected eight electrical treatments representative of rectangular pulse frequencies and durations commonly available in commercial electrofishing units. These included continuous DC (duty cycle = 100%); pulsed DC 110 Hz, 6 ms (duty cycle = 66%); pulsed DC 110 Hz, 1 ms (duty cycle = 11%); pulsed DC 60 Hz, 6 ms (duty cycle = 36%); pulsed DC 60 Hz, 1 ms (duty cycle = 6%); pulsed DC 15 Hz, 6 ms (duty cycle = 9%); pulsed DC 15 Hz, 1 ms (duty cycle = 1.5%); and Coffelt's CPS (duty cycle = 12%). Coffelt's CPS (complex pulse system) was evaluated because the manufacturer claims that this system reduces myoclonic jerks and trauma by merging high-pulse frequency with a low-frequency pattern. The CPS delivers a fixed complex pulse pattern consisting of three 240-Hz, 2.6-ms rectangular pulses, each separated by 1.6 ms, and repeated 15 times/s.

Peak voltage (V_{pk}), pulse frequency, and pulse duration were measured within the energized field with a Tektronix THS720A oscilloscope (Tektronix, Inc., Oregon). Following Kolz and Reynolds (1989), V_{pk} was used to calculate power density (P_w):

$$P_w = C_w \cdot \left(\frac{V_{pk}}{d}\right)^2, \qquad (2)$$

where d is the distance between the electrodes (i.e., 65 cm).

We applied the eight electrical treatments to bluegills, channel catfish, and largemouth bass of various sizes. However, limited fish availability did not allow application of all electrical treatments to a balanced combination of species and sizes. Before testing, fish were seined from holding ponds, held in concrete raceways for at least 48 h, and maintained in good condition on a diet of live or artificial food, depending on the species. During testing, a single fish was indiscriminately dipped from the holding tank, transferred to the test tank, and confined in the area between the two electrodes. After allowing 3–10 s for the fish to orient and, then, when the fish was positioned perpendicular to either electrode, the current was switched on for 15 s. The set of fish within a treatment (e.g., continuous DC) was exposed to power densities that ranged from zero (controls) to levels exceeding those needed to immobilize them within 3 s (one fish per test power density). Power density was incremented by raising voltage in steps that ranged from 1.05 times to 2.2 times per step, depending on voltage level and electrical treatment. The immobilization response (i.e., halt swimming within 3 s) was recorded as 0 for no immobilization and 1 if a fish was immobilized. Also, we recorded whether each test fish exhibited narcosis or tetany by the completion of the 15-s period. The 3-s period estimated the time within which if a fish were not immobilized, it would probably escape the electrical field; the 15-s period estimated the maximum amount of time that a fish would be exposed to electricity in an actual field setting. The number of fish tested per treatment set ranged from 11 to 28, including 2–4 controls (i.e., no power density applied). Following treatment, each fish was transferred to an aerated 38-L holding tank (one fish per tank) and held for 18 h to allow potential hemorrhages to manifest and to determine short-term mortality.

Injury assessment.—Following the 18-h holding period, each tank was checked for incidence of fish mortality. Fish that remained alive after the holding period were euthanatized in a lethal concentration of Finquel (>100 mg/L; active ingredient is tricaine methanesulfonate or MS-222; Argent Chemical Laboratories, Inc., Washington). All specimens were kept on ice for transport to the Mississippi State University College of Veterinary Medicine, where they were radiographed within 2 h. Radiographs were examined for evidence of spinal injury (i.e., compression, misalignment, or fracture of the vertebral column). A certified radiologist reexamined radiographs to verify interpretation of spinal injury and to help differentiate congenital abnormalities and past injuries from those due to electroshock exposure. Immediately following radiography, all fish were necropsied to evaluate tissue hemorrhage (i.e., bleeding of blood vessels and capillaries). Necropsy included filleting the length of the body from just posterior to the pectoral fins, along the rays and spine, to the caudal peduncle. For reference, digital photographs of all filleted fish (lateral view) were taken. Mortality, spinal injury, and tissue hemorrhage were scored binarily: 0 = no hemorrhage, no spinal injury, or no mortality; 1 = hemorrhage, spinal injury, or mortality occurred.

Funds were not available to evaluate injuries in the smallest size-class for the three species treated with the 60 Hz treatment. Thus, these fish were not radiographed, but hemorrhage was evaluated when possible. However, we evaluated mortality in all individuals that were not budgeted for injury assessment because there was no cost involved with holding fish overnight.

Data Analyses

Percentages of fish exhibiting hemorrhage, spinal injury, and mortality were calculated by species and size-class. These calculations were limited only to fish immobilized within 3 s. Fish not immobilized within 3 s were excluded from the data and from statistical analyses on hemorrhage, spinal injury, and mortality because electrofishing is commonly conducted with power densities high enough to induce immobilization. Thus, including fish that were not immobilized would have misleadingly reduced overall levels of injury and mortality.

Effects of fish size, species, and duty cycle.—The effects of size, species, and duty cycle on percentage hemorrhage, spinal injury, and mortality were evaluated through analysis of covariance (ANCOVA; SAS Institute 1996). The model examined those effects and their interactions on the three categories of injury. Fish volume was selected to describe size because it had been previously identified as the size descriptor best related to the level of electric power required for immobilizing fish (Dolan and Miranda 2003), and produced the smallest residual errors; nevertheless, fish lengths and weights were strongly correlated with fish volume. Using Image Tool software (University of Texas Health Science Center, San Antonio), the volumes were estimated from digital photographs of a subsample (N = 16–22/species) of fish representative of the average size included in each treatment. To satisfy assumptions of linearity and homogeneity of variances, we transformed the injury response variables (arcsine of square root) and the fish size and duty cycle covariates ($\log_{10}$). The ANCOVA model was fit separately to each of the three response variables (i.e., hemorrhage, spinal injury, and mortality). Multiple linear contrasts (SAS Institute 1996) were used to test for differences in hemorrhage, spinal injury, and mortality across significant main effects or interaction variables. We relaxed significance testing to $\alpha = 0.2$ because making a type II error (i.e., accepting a null hypothesis of no effect when the alternative is true) was a major concern due to the nature of the effect being tested.

Effect of behavioral endpoint on injury and mortality.—The behaviors displayed by fish at the conclusion of the 15-s period (i.e., narcosis or tetany) were used to categorize injury. Fisher's exact tests (SAS Institute 1996) were applied to test whether incidence of hemorrhage, spinal injury, and mortality differed between fish displaying narcosis and tetany. Similarly, fish were separated as to whether they lived or died during the 18-h holding period after electroshock treatment, and hemorrhage and spinal injury were compared between these two categories with Fisher's exact test.

Results

In all, 737 treatment fish and 122 control fish were tested. Of the treatment fish, 611 (83%) were immobilized within 3 s and included in analyses. Incidence of hemorrhage was evaluated in 83% of the fish immobilized, spinal injury in 79%, and mortality in 100%. Water temperature ranged from 16–28°C (mean = 24°C) across treatment sets. Although we strived to maintain ambient conditions as constant as practicable, variability in water temperature had to be accepted owing to the seasonal availability of test fish. If the range of experimental temperatures influenced reaction thresholds, it would have added random noise that reduced our ability to detect treatment effects. Specific conductivity was relatively invariable at 195 μS/cm (SD = 4) throughout the study. However, due to fluctuations in water temperature, ambient water conductivity ranged from 161 to 213 μS/cm. Peak voltages ranged from 12 to 1,100 V, and peak power densities ranged from 7 to 55,560 μW/cm^3.

No hemorrhage, spinal injury, or mortality was observed in control fish. Injuries in treatment fish normally occurred mid-dorsally along the vertebral column. Spinal injury usually consisted of the compression of 2–3 vertebrae, without discernible fractures. Hemorrhages ranged from 1 to 3 vertebrae in diameter. Mortalities occurred over the first 3 h of the 18-h holding period, but many fish were probably killed during the 15-s treatment because fish often appeared to not recover from tetanus.

Incidence of hemorrhage averaged 3% and ranged from 0% to 25% (Table 1). Hemorrhage incidence differed among species but was not correlated with duty cycle or fish volume (Table 2). Largemouth bass had the greatest vulnerability to hemorrhage, whereas bluegills had the least. Channel catfish were intermediate between the other

TABLE 1.—Incidence (%) of hemorrhage, spinal injury, and mortality in 611 fish treated (i.e., electroshocked) with various duty cycles and with power densities high enough to immobilize them within 3 s. Values within brackets represent the frequency–pulse duration combination, those within braces represent the mean total length (mm) and volume (cm^3), and those within parentheses represent the number of fish treated with each duty cycle. Blanks indicate a test was not conducted. No hemorrhages, spinal injury, or mortalities were observed in 122 control fish (i.e., not electroshocked).

Species and injury	Duty cycle 100% [DC]	66% [110–6]	36% [60–6]	12% [CPS[a]]	11% [110–1]	9% [15–6]	6% [60–1]	1.5% [15–1]
Channel catfish {162; 31}	(17)	(14)	(18)	(10)	(16)	(17)	(15)	(11)
Hemorrhage	6	0		0	0	0		0
Spinal injury	0	0		0	0	0		0
Mortality	0	0	0	10	0	6	0	0
Channel catfish {319; 319}	(16)	(14)		(14)	(15)	(15)		(13)
Hemorrhage	6	0		0	20	0		0
Spinal injury	0	0		0	0	0		0
Mortality	6	14		29	0	0		15
Bluegill {67; 12}	(10)	(13)	(25)	(10)	(14)	(23)	(15)	(14)
Hemorrhage	0	0		0	0	0		0
Spinal injury	0	0		0	0	0		0
Mortality	0	0	0	50	0	52	7	50
Bluegill {158; 105}	(12)	(13)		(10)	(12)	(18)		(12)
Hemorrhage	0	0		0	8	0		0
Spinal injury	0	0		20	0	0		8
Mortality	0	0		0	8	0		0
Largemouth bass {71; 6}	(11)	(12)	(14)	(12)	(12)	(24)	(14)	(13)
Hemorrhage	0	17	14	0	25	0	7	0
Spinal injury	0	0		0	0	0		0
Mortality	0	0	29	75	0	54	14	46
Largemouth bass {217; 190}	(13)	(9)		(10)	(13)	(9)		(11)
Hemorrhage	8	0		10	0	0		0
Spinal injury	0	0		10	15	22		18
Mortality	0	0		0	0	0		18
Largemouth bass {267; 273}					(12)		(16)	
Hemorrhage					0		6	
Spinal injury					8		0	
Mortality					0		0	

[a] CPS = Coffelt's complex pulse system, a commercial product merging high pulse frequency with a low-frequency pattern.

two species and did not differ significantly from largemouth bass or bluegills (Table 2).

Incidence of spinal injury averaged 3% and ranged from 0% to 22% (Table 1). No spinal injuries were recorded for small largemouth bass, small bluegills, small channel catfish, or large channel catfish. The greatest levels of spinal injury were exhibited by large largemouth bass and large bluegills. Spinal injury differed among species, was inversely related to duty cycle, and directly related to volume (Table 2). Interactions between volume and duty cycle and species and duty cycle reflected the absence of injury to small fish and large channel catfish, as well as the increasing level of injury in large largemouth bass and large bluegill as duty cycle decreased.

Incidence of mortality averaged 10% and ranged from 0% to 75% (Table 1). Mortality depended on species and was inversely correlated with volume (Table 2). However, an interaction between volume and species (Table 2) suggested that the effect of volume depended on species. For largemouth bass and bluegills, mortality increased as volume decreased, but the reverse was true for channel catfish. Moreover, mortality was inversely related to duty cycle, but an interaction between duty cycle and volume indicated that the effect of duty cycle depended on fish size. This interaction reflected the increased incidence of mortality at low duty cycles for small fish but a lack of relation across duty cycles for large fish.

The 1% incidence of hemorrhage for fish narcotized by the end of the 15-s period was significantly lower than the 4% for tetanized fish (Table

TABLE 2.—Analysis of covariance models for the percentage of hemorrhage, spinal injury, and mortality for fish of different species and volumes treated (i.e., electroshocked) over a range of duty cycles. Signs in parentheses indicate direction of a relationship having a $P \leq 0.20$. Pairwise comparisons are indented.

Variable	F	df	$P > F$
Model: Hemorrhage			
Species	2.56	2, 35	0.09
Bluegill versus channel catfish	0.77	1, 35	0.47
Bluegill versus largemouth bass	4.97	1, 35	0.03
Channel catfish versus largemouth bass	1.31	1, 35	0.29
Volume	0.07	1, 35	0.79
Duty cycle	1.71	1, 35	0.22
Model: Spinal injury			
Species	6.34	2, 30	<0.01
Volume (+)	7.98	1, 30	<0.01
Duty cycle (−)	8.08	1, 30	<0.01
Duty cycle × volume (−)	7.64	1, 30	<0.01
Duty cycle × species	4.10	2, 30	0.02
Bluegill versus channel catfish	3.88	1, 30	0.06
Bluegill versus largemouth bass	1.10	1, 30	0.30
Channel catfish versus largemouth bass	8.09	1, 30	<0.01
Model: Mortality			
Species	4.04	2, 36	0.02
Volume (−)	8.95	1, 36	<0.01
Duty cycle (−)	11.85	1, 36	<0.01
Duty cycle × volume (+)	8.71	1, 36	<0.01
Volume × species	6.12	2, 36	0.01
Bluegill versus channel catfish	5.53	1, 36	0.03
Bluegill versus largemouth bass	0.02	1, 36	0.89
Channel catfish versus largemouth bass	8.49	1, 36	<0.01

3). Similarly, incidence of spinal injury was 1% for fish that were narcotized and 3% for those that were tetanized, but this difference was not statistically significant. Mortality for narcotized fish was 5%, which was significantly lower than the 14% experienced by tetanized fish. Of the fish that survived electrical treatment, hemorrhages were detected in 4% and spinal injuries in 3%. Both of these values were not significantly higher than the 0% hemorrhage and spinal injury recorded in fish that did not survive electrical treatment.

Discussion

Testing was conducted under controlled laboratory conditions to avoid the inconsistencies associated with data collected in a field setting. A major concern in testing the effects of electrofishing is controlling for variable voltage gradients characteristic of electric fields generated in complex aquatic environments. One approach to avoid this variability would be to design an apparatus to confine fish to standard test positions selected within the heterogeneous field. Such an approach would be equivalent to testing fish in a homogeneous field like the one replicated in our tank, where we experimentally reproduced a set of voltage gradients, one at a time. Thus, although our experimental setting may be misconstrued as unrealistic, it can produce results applicable to electrofishing operations in the field.

TABLE 3.—Percent hemorrhage, spinal injury, and mortality for fish narcotized or tetanized within the 15-s treatment (i.e., electroshock) periods and the percent hemorrhage and spinal injury for fish found dead or alive by the end of an 18-h postshock holding period. A Fisher's exact test was applied to compare percentages; significance was set at $\alpha = 0.20$.

		Status by end of 15 s			Status by end of 18 h		
Injury	N	Narcosis	Tetany	P-value	Alive	Dead	P-value
Hemorrhage	509	1	4	0.14	4	0	0.24
Spinal injury	480	1	3	0.47	3	0	0.62
Mortality	611	5	14	<0.01			

Incidence of electrofishing-induced injury and mortality depended on fish size, species, and duty cycle. Differences due to size are most likely linked to disparities in muscle mass and muscle composition. Larger fish often have well-developed muscles that contract forcefully and may severely compress the vertebrae to cause spinal injury and associated hemorrhage (Lamarque 1990). Moreover, large fish tend to have a higher proportion of white muscle fibers that are larger than red muscle fibers and contract more powerfully (Helfman et al. 1997). We observed spinal injury and hemorrhage most often on or near the vertebral column in dorsal–anterior regions of the trunk, where the strongest muscle contractions were likely to occur. Differences due to species probably derive from anatomical and morphological attributes linked to species adaptations. For example, channel catfish possess a dense, heavy skeleton (Evans 1998) to support a benthivorous feeding strategy (Pflieger 1997), whereas fish that feed within the water column, such as bluegills and largemouth bass, have a lighter, less-ossified skeleton. Also, the coarse scales of centrarchids may make them less susceptible to the effects of electroshock compared with the vestigial-scaled channel catfish (Reynolds 1996). Differences due to duty cycle reportedly reflect changes in response to varied electrical stimuli by the fish's nervous system (Lamarque 1990; Sharber et al. 1994; Sharber and Black 1999). In practical field electrofishing, differences among species are difficult to control because electrofishing affects all species exposed to the electrical field; however, the user has complete control over duty cycle and partial control over the size of fish targeted (Dolan and Miranda 2003).

Duty cycle can be controlled by manipulating pulse frequency and pulse duration using the instrumentation provided by most commercial electrofishing equipment. As duty cycle is decreased, increasingly higher power densities are required to immobilize fish (Miranda and Dolan 2004, this issue), which in itself may be sufficient to cause injury. But in addition, as duty cycle decreases there is a decreasing margin of difference between the electrical power required to narcotize fish and that required to tetanize them, to the extent that the power needed to narcotize fish within 3 s will almost inevitably produce tetany within 15 s (Miranda and Dolan 2004). In addition, we observed that fish exposed to low duty cycles vibrated or quivered vigorously. This vibration was consistent with the symptoms (twitches, jerks, and convulsions) of epileptic seizure described by Sharber and Black (1999), who stated that seizures could be induced in many vertebrates (including fish) by passage of electrical current through the brain. Epileptic seizure has been suggested as cause for gross physical injuries, such as spinal injury (Sharber et al. 1994), so seizures also may result in less detectable injuries (e.g., organ, tissue, and cell injury) that may eventually lead to death. High power density requirements and seizures, coupled with the need to tetanize fish to achieve immobilization, probably contribute to the harmful effects of low duty cycles. Because spinal injury and mortality were inversely related to duty cycle, electrofishing with intermediate to high duty cycles should minimize detrimental effects.

Substantially higher power densities are required to immobilize small fish compared with large fish (Edwards and Higgins 1973; Dolan and Miranda 2003). These discrepant requirements normally translate into unequal size efficiencies, electrofishing being more effective for immobilizing large fish (Dolan and Miranda 2003). High mortality of small centrarchids was observed in the present study. Similarly, Bardygula-Nonn et al. (1995) observed higher mortality in small bluegills ($<$10 cm) shocked at a low duty cycle compared with other species. The high rate of mortality in small fish was possibly due to exposure to elevated peak power densities required to immobilize small individuals. Thus, limiting power output to that necessary for immobilizing large fish only, could potentially reduce or eliminate high levels of mortality associated with electrofishing small fish with low duty cycles. Nevertheless, the electrical field created between electrodes under field conditions is heterogeneous, varying in strength by several folds, depending on electrode sizing and positioning (Reynolds 1996). Consequently, the operator can control the power transmitted between electrodes but often may not be able to control exposing fish to high power densities that are commonly encountered in the proximity of electrodes. Novotny (1990) identified approaches for reducing excessive field strengths surrounding electrodes.

Traditionally, field electrofishing has been considered most effective when conducted with settings that have maximum tetanizing effects (Lamarque 1990). Our observations indicate that regardless of duty cycle, tetanized fish exhibited more hemorrhage and mortality. Persistence of tetany after the interruption of current may prevent resumption of respiration, leading to suffocation and death. Given that injury levels were less in fish that were narcotized but not tetanized, operating equipment to produce power densities that induce narcosis rather than tetany can reduce injury and mortality. Such an operational approach simplifies electrofishing by requiring adjustment of electrical output through observation of fish behavior in the electrical field rather than through in-water measurement of electrical variables.

Mortality was not related to gross scale injuries because hemorrhage and spinal injury were similar in fish that initially survived electroshock and those that died. This finding implies that the mechanisms that cause gross physical injuries, such as hemorrhage and spinal injury, may not be the same as those that cause immediate mortality. Similarly, Spencer (1967) reported a lack of correlation between incidence of spinal injury and mortality of bluegills, and Hudy (1985) stated that more vertebral injuries were observed in trout that survived electroshock than in those that died. Taylor et al. (1957) found that mortalities of rainbow trout induced by electrofishing were almost never associated with ruptured blood vessels, injury to bones or organs, or other trauma, but instead, hypothesized that mortality of trout appeared to result from factors that were not visible either grossly or microscopically. Barton and Grosh (1996) and Barton and Dwyer (1997) determined that electric current can alter blood constituents and suggested that the stress associated with these changes may reduce survival. Many of the fish mortalities in our experiment appear to have occurred rapidly within the 15-s treatment period. Potentially, rapid immobilization and death prevented the physical stress (i.e., hemorrhage and spinal damage) experienced by fish that survived, but physiological stresses to the fish may have contributed to mortality. Future research to pinpoint an exact cause of death for fish exposed to electric current may need to focus on exploring injury at smaller scales, through examination of vital organs such as the respiratory and circulatory systems.

Minimizing the risk of harm to fish during population surveys is clearly an important goal of fish sampling, and efforts should be made to adjust electrical settings to reduce negative effects. Our results suggest that continuous DC or pulsed DC with intermediate to high duty cycles may be the best choices for reducing electrofishing harm to warmwater fish. Power output should be managed to induce narcosis and avoid tetany because tetany appears to be associated with higher injury rates. Tetany is avoided more easily with high duty cycles because of a wider margin of difference between the electrical power required to narcotize fish and that required to tetanize them (Miranda and Dolan 2004). Manipulation of maximum power output to target immobilization of large individuals would avoid the peak powers required to immobilize small individuals and, thus, reduce overall mortality rates. However, modifications to the electrode system may be necessary to avoid high power densities that commonly occur in the proximity of electrodes.

Collecting fish with electric current and subsequent handling is inherently risky because injury and mortality to fish can result. Generally, negative side-effects are thought to have minimal effects on fish populations (Ainslie et al. 1998; McMichael et al. 1998). From an ethical standpoint, it may be important to minimize electrofishing injury and mortality whenever possible because we possess the ability to do so. Moreover, there are instances (e.g., mark–recapture studies, sampling threatened and endangered fishes) in which electrofishing should be employed with great caution or simply avoided. Despite the risks associated with electrofishing, it remains a valuable tool for inland fisheries management when applied judiciously.

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